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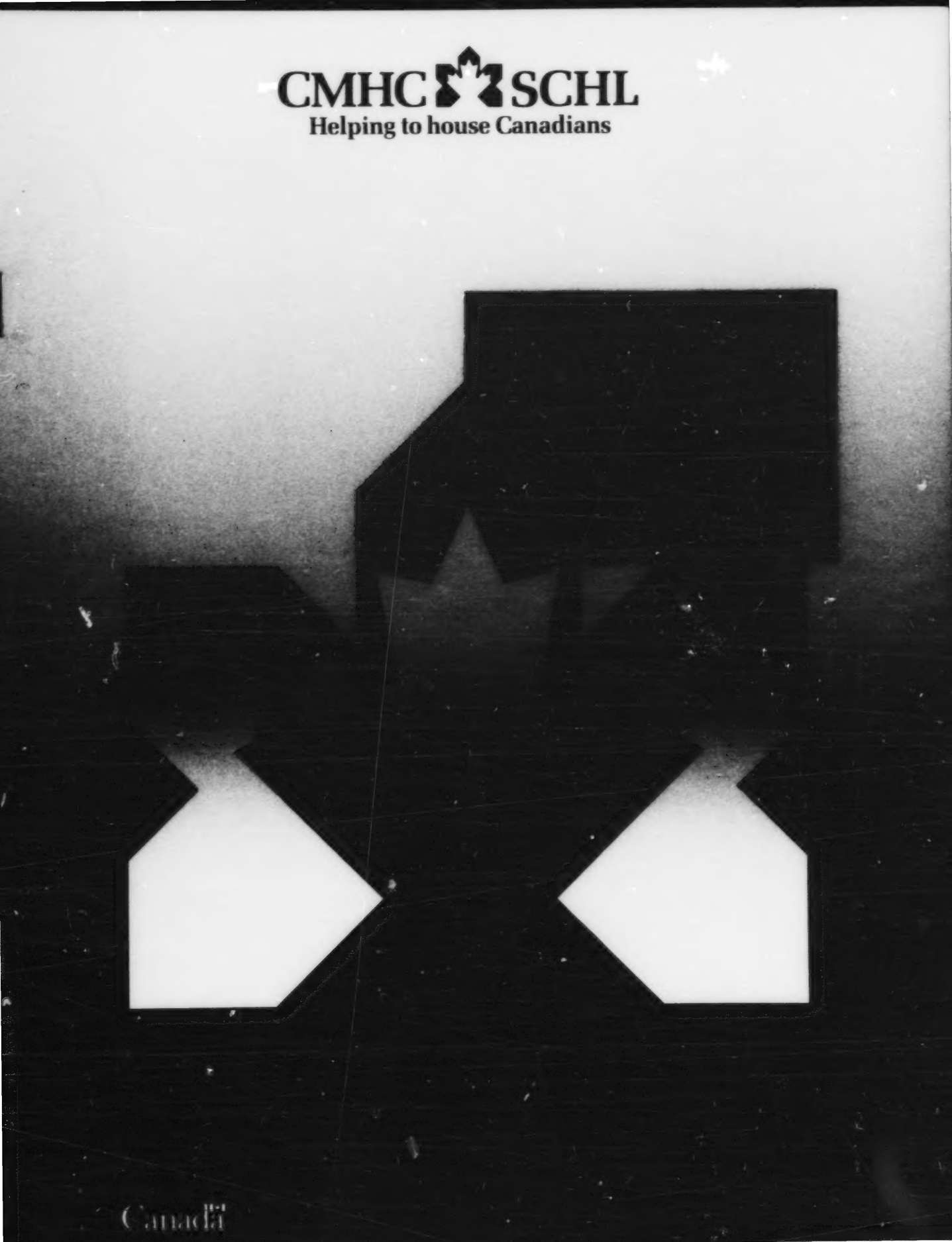

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EARTHQUAKE DAMAGE IN THE SAN FRANCISCO AREA AND PROJECTION TO GREATER VANCOUVER

JANUARY 1990

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CLIENT REPORT

for

Canada Mortgage & Housing Corporation
National Office, 682 Montreal Road
Ottawa, Ontario K1A 0P7

Earthquake Damage in the San Francisco Area and Projection to Greater Vancouver

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EXECUTIVE SUMMARY

The earthquake that hit the San Francisco area on October 17, 1989 produced damage to buildings, to transportation facilities, and to services in the order of $10 billion (U.S.) and loss of life of over 60 people. This earthquake can be used as a model for the seismic risk faced by the greater Vancouver area because of many similarities with a design earthquake in the Vancouver area. These similarities include earthquake magnitude and duration, location relative to population centres, range of recorded ground accelerations, and similarities in type of construction. On the other hand, account needs to be taken of some expected essential differences, among them the level of seismic design forces for engineered construction and for residential requirements for buildings, extent of soft soil deposits, and the specific ground accelerations measured and soil amplifications observed at particular locations. These factors point to the conclusion that the expected damage in Vancouver from a "design earthquake" that is implied in the National Building Code of Canada would be somewhat greater than that observed in the San Francisco region in October 1989.

With a few exceptions, the experience from San Francisco re-affirms the level of major damage predictions that were made in IRC's previous study for CMHC, before the San Francisco area earthquake occurred. However, reductions in loss ratio estimates were thought appropriate for "low and medium rise residential and office" buildings to 2-5%, and "communication systems" to 5-10%.

The San Francisco experience underlines the role of soil conditions as an important factor in the seismic risk to a building and its inhabitants. Site amplifications were clearly evident on soft soils, and liquefaction with accompanying loss of bearing strength occurred on sites that experienced firm ground accelerations of about one half those of the "design earthquake" acceleration for Vancouver. More detailed mapping, so-called "micro-zonation", of potential hazardous areas should be carried out.

As a result of the experience in the San Francisco area, potential shortcomings in the 1985 National Building Code of Canada were identified in the seismic requirements for Residential Construction (Part 9). These possible shortcomings concern lateral bracing, beam splice ties over supports, and anchorage and reinforcing of chimneys. The potential risks posed by buildings that have inadequate seismic resistance should be addressed.

Emergency preparedness in the San Francisco area was at a high level and this paid dividends in the rescue efforts, in dealing with the chaos created by the earthquake, and in restoring normal functions within a short time after the quake. This could serve as a model for a preparedness plan for the Vancouver area and other population centres located in seismically active areas in Canada.

EARTHQUAKE DAMAGE IN THE SAN FRANCISCO AREA AND ITS PROJECTION TO GREATER VANCOUVER

1. INTRODUCTION

On October 17, 1989, 17:04 Pacific Daylight Time (PDT), a strong earthquake, called the "Loma Prieta" earthquake, of Magnitude M_S=7.1 on the Richter scale, shook the entire San Francisco Bay area. Eight days later, an IRC team consisting of Dr. K.T. Law (Team Leader) and Dr. A.M. Jablonski was dispatched to San Francisco. The team was augmented by three seismic experts from the other organizations: Mr. J. Tang, Ontario Hydro, Mr. J.-R. Pierre, Hydro-Quebec and Dr. D.T. Lau, Carleton University. The prime objective was to determine the nature and extent of the damage to housing and lifelines in the San Francisco Bay Area with a view to predicting the expected impact of a similar magnitude earthquake in the greater Vancouver area, and to reassess the damage picture projected for Vancouver in a previous report to CMHC. The IRC team got an affiliation to Earthquake Engineering Research Institute (EERI) in El Cerrito for their post-disaster study and thereby obtained immediate access to areas affected by the earthquake. The generous assistance of EERI, the US Geological Survey, and numerous local officials in the affected areas is gratefully acknowledged.

2 SYNOPSIS OF LOMA PRIETA EARTHQUAKE AND ITS IMPACT IN THE SAN FRANCISCO AREA

The Loma Prieta earthquake was caused by the rupture of the section of the famous San Andreas fault extending from the Highway 17 crossing (near Lexington Dam Reservoir) north of the Pajero Gap (near the Highway 101 crossing) at the south. The epicentre of this earthquake was located approximately 16 km northeast of the city of Santa Cruz in the Forest Nisene Marks State Park in the Santa Cruz Mountains (Fig. 1). The hypocentral depth was about 18.5 km, which is relatively deep for most events associated with the San Andreas fault. The fault movement includes not only typical horizontal component of slip, but also a significant thrusting of the southwest side up and over the northeast side [1]. Within a period of twelve days after the main shock, 80 aftershocks of magnitude 3.0 and larger were recorded. The largest aftershock, Magnitude 5.2, occurred 37 minutes after the main shock. The second largest aftershock, Magnitude 5.0, occurred Thursday, November 2, 1989. Seismologists advised that additional aftershocks, although generally becoming smaller and smaller, could be expected in the next few weeks to months after the earthquake. Because of this continuing hazard, special caution had to be exercised during the inspection in and around damaged structures [2].

This was the largest magnitude earthquake in northern California since the San Francisco earthquake of April 18, 1906 of Magnitude M_S=8.3. The Loma Prieta earthquake has been estimated as one of the largest natural disasters in U.S. history, exceeding the $8 billion losses resulting from Hurricane Hugo [3,4,8]. The Loma Prieta earthquake caused severe damage to a number of engineered structures: collapsed the Cypress Street viaduct of the Interstate Highway 880, (also called Nimitz Freeway), where dozens of motorists were killed; collapsed the section of the San Francisco-Oakland Bay Bridge on the Oakland side of the bridge where the earthquake caused displacement of 18 cm; heavily damaged a number of bridges and highways (among them San

Lorenzo River Bridge on Highway 9 and Strive Slough Bridge on Highway 1 near Watsonville). The nine counties, i.e. San Francisco, Alameda, San Mateo, Santa Cruz, Santa Clara, San Benito, Monterey, Contra Costa and Marina, were affected and reported extensive damage. A number of cities were hit, including San Francisco and Oakland, but the major areas of destruction were limited to several pockets associated with soft soil deposits, especially fill areas. The earthquake caused ground failures in many areas, including soil liquefaction, landslides, soil lateral spreads and ground cracks. It also has been reported to have caused 66 confirmed deaths, more than 3200 injuries and estimated damage of $10 billion [3,4].

3. STRONG MOTION SEISMOGRAPH DATA

About 40 km of the San Andreas fault slipped during the Loma Prieta earthquake. This triggered all seismographic stations in the San Francisco Bay area. Two major networks have been installed, one by the Division of Mines and Geology, State of California (DMGSC) under the California Strong Motion Instrumentation Program (CSMIP) and other by the U.S. Geological Survey in Menlo Park. Some measurements were recorded by other networks, e.g. seismographic Stations of the University of California at Berkeley and Stanford University [5,6,7,8]. A summary of the strong-motion measurements is presented in Appendix A.

Figure 2 presents the measured peak horizontal acceleration vs. epicentral distance. The attenuation tendency is also indicated. High peak acceleration on Bay mud were recorded in Oakland near I-880 and at Presidio, San Francisco, close to heavily damaged area in Marina District.

A contour map based on the recorded peak accelerations is presented in Fig. 3.

4. EFFECTS OF GROUND CONDITIONS

Widespread earthquake damage to structures and buildings is generally a direct result of the intensity and type of ground shaking. Local ground conditions can change the characteristics of earthquake motions that exist at the bedrock. In particular, thick deposits of compressible soils can raise the intensity of motions in a certain frequency range leading to severe damage. Such deposits are abundant in the San Francisco Bay region and exist in three different types: fills, Bay mud and alluvium.

Fills are man-made deposits normally loose in nature. For example, in the Marina District, centrally located on the northern coast of the City of San Francisco, the fills were placed hydraulically. They are of very loose, uniform sand with sea shells. The Bay mud consists mostly of recent deposits (8,000 years and younger) of soft plastic carbonaceous clay, silt and minor sand inclusions. It is loose with moisture content normally exceeding 50% and may be as thick as 40 m. Shear wave velocities in this deposit range from 90 to 130 m/s. The alluvium corresponds to an older Bay sediment unit. It consists mostly of silty clay, silty clayey sand, sand and gravel. It has generally a moisture content of less than 40% with thickness reaching 600 m. The shear wave velocities in this deposit increase with depth and at the surface the value is about 200 m/s. The distribution of Bay mud and alluvium is shown in Figure 4.

During the 1989 Loma Prieta earthquake these deposits responded in three ways causing serious damage or collapse of structures and buildings: amplification of ground motions, liquefaction failure, and densification.

4.1 Amplification of Motions

The amplification of earthquake motions is a complex process and depends on soil properties, thickness, frequency content of motions and local geological settings. For a given earthquake and geological setting, the amplification increases with increase of soil compressibility and with increase of soil thickness. Since soil compressibility is inversely proportional to the shear wave velocity, amplification of motion is larger in the Bay mud than in the alluvium because the former has a lower shear wave velocity. The highest amplification in the Bay region, therefore, will come from thick deposits of Bay mud.

Structures founded on these compressible deposits have been subject to high horizontal excitation during the earthquake. All the major damages in San Francisco City and Oakland City occurred on these deposits. Many residential houses in the Marina District sustained severe damage and some even collapsed, mainly because of the high amplification due to the Bay mud and the hydraulic fill. Houses similar to the collapsed ones just outside the Marina District suffered from slight damage because of the lower excitation. The pier supporting the collapsed section of the Bay Bridge was founded on the Bay mud. The collapsed Cypress section of the Nimitz Freeway (I-880) was founded also on the Bay mud, while the other non-collapsed section was founded on alluvium. This observation supports the contention that Bay mud yields a higher amplification than the alluvium. Also, a number of multi-storey steel frame buildings and reinforced concrete buildings in downtown Oakland suffered from structural damage where alluvium prevails. In downtown Santa Cruz, where land was reclaimed with man-made fills, 85% of the unreinforced masonry buildings were damaged.

4.2 Liquefaction Failure

Liquefaction failure is a process in which soft saturated granular soil is transformed to a liquid as a result of earthquake shaking or by other dynamic disturbance. When this happens the soil beneath the surface is liquefied and, under pressure from the overburden, tends to eject the water and soil mixture through the ground surface. This will result in cracking of ground, ground heave, sand boils, building collapse and differential settlement. All these phenomena were observed over an extensive area (Figure 5) ranging from very near the epicentre to more than 100 km away. Examples of liquefaction failures are shown in Figures B20 to B23 in Appendix B.

In the Marina District, liquefaction failure is widespread. More than 20 sand boils were noted by the visiting team. Differential settlement, bearing capacity failure, pavement damage and buckled sidewalks were observed. Buried utilities including gas lines were broken and led to spectacular fires. The material that flowed to the surface was a dark grey uniform sand with occasional sea shells indicating that the hydraulic fill placed on site liquefied during the earthquake. The whole area was evacuated and public access was restricted.

4.3 Densification

Loose granular deposit, both saturated or unsaturated, may densify leading to considerable settlement even without the phenomenon of liquefaction. A good example is found at Embarcadero Freeway on the northeastern coast of San Francisco. Here fills were placed on top of Bay mud. The structure of the freeway was damaged to the point of near collapse, again due to ground motion amplification. The footings for the structures and nearby buildings are apparently founded on pile-foundations. These footings probably vibrated during the earthquake but suffered from little permanent settlement. The paved ground surface, however, settled about 15 cm relative to the footings because of densification of the fill (Figure B24).

4.4 Other Ground Problems

A large number of landslides and rockfalls were reported in the Santa Cruz Mountains near the fault rupture zone. Many of these landslides were partly caused by rain that came after the earthquake. Highway 17, one of the two main highways into Santa Cruz from the north, was partly closed. A number of single family houses were destroyed.

Signs of distress in a number of dams were reported. The Lexington earth dam suffered from some cracks. The abutment of the Elsman dam sustained some cracks. About 1.5 km of San Lorenzo levee in Santa Cruz suffered from cracks. Another 1.5 m levee along the Pajaro River outside Watsonville was damaged. Evidence of liquefaction failure was reported there.

5. PERFORMANCE OF BUILDINGS

The impact of future earthquakes is usually evaluated based on the available data from past events. The Loma Prieta earthquake in the Santa Cruz Mountains provided an extraordinary opportunity to test various types of building structures, from single-family dwelling houses and medium size building in the Santa Cruz area to high-rise buildings in San Francisco and Oakland. In general their performance depended on a number of factors including type of the structure, year of construction, lateral resistance and local ground effects. This section covers briefly the performance of various types of buildings in earthquake affected areas. Reference is made to epicentral distance and closest recorded peak horizontal acceleration.

Structural damage was widespread and sometimes of a complicated nature. Aftershocks have augmented damage in several buildings. It has not been possible to visit several locations of damaged buildings, but a brief description of representative damage patterns is presented below. Reference is made in this section to photographs in Appendix B.

5.1 Wood Frame Housing

Two types of wood frame houses sustained heavy damage. The first type could be classified as single-family dwellings of various forms. They are located in the epicentral area (50 km radius). The second type is associated with 3-4 storey wood frame apartment houses and also 2-storey townhouses in Marina District in San Francisco about 100 km from the epicentre.

5.1.1 Epicentral Area

"Cripple" foundation walls (or "pony" walls) failed in many old wood frame houses in the epicentral area (e.g. in Watsonville and in Los Gatos) causing serious damage. Cripple walls are stud walls which form the connections between foundations (concrete or masonry) and the first floor framing (see Fig. 6). They are usually short, but in some modern wooden houses could reach a height of one full storey. Older buildings of 50 years or more appeared to not have enough lateral resistance to withstand severe shaking.

Improper bracing and inadequate connections to the foundations as well as to the first floor framing had caused them to be moved laterally off their foundations. The cripple walls were in some cases laying flat on their side. An example of the cripple wall failure is presented in Figs. B2 and B3. A residence, approximately 60 years old, at 114 Brennan Street in Watsonville is situated about 12 km of the epicentre. This area experienced high frequency shaking, the acceleration reaching 0.40g during approximately 16 seconds. Failing cripple walls shifted the overall wood frame structure off the foundations and caused the partial loss of its integrity. Although these walls were sheathed or sided with horizontal boards, nailing was sparser than required by the code. The panels could not provide the lateral resistance to prevent racking and in some instances this lead to the complete failure of cripple walls. Also, large openings (e.g. porches) collapsed due to lack of lateral resistance and settlement of the foundations. Figure B4 shows a complete failure of a cripple side wall of the residence, with the porch completely destroyed. Another example of damage to a single family wood frame house is shown in Figs. B5, B6 and B7. This is an old residence with cripple wall which is not anchored to the foundation. This house was moved laterally by about 45 cm. The porch partially collapsed and caused damage to the ceilings (Figs. B5 and B7).

Modern wooden houses with and without cripple walls performed well unless they were situated on ground fissures [10]. Most of these buildings were built according to recent codes. However, some houses with large openings like garage doors situated under the living area or with other irregularities sustained substantial damage (e.g. Los Altos Hills near Palo Alto, about 50 km from the epicenter and where the acceleration reached about 0.38g). In some cases the perimeter band joist was anchored to the foundation using hold-down anchors with log screws into the band joist. The lag screws failed in withdrawal from the joist due to severe shaking [10]. In general, poor connections or lack of structural continuity in the design were the prime reasons of damage in wood frame houses.

5.1.2 Marina District, San Francisco

The largest damaged area outside the epicentral region was concentrated in the Marina district in San Francisco. This area along with some portions of downtown around the Market Street are situated on deep soft deposits, of fill and Bay mud. The layers of sand liquefied during severe shaking, resulting in upheaving of streets and sidewalks and settlements. The shaking was amplified in a similar way to what happened during the Mexico City earthquake of 1985. The highest acceleration nearby, 0.21g, was recorded in Presidio, a few blocks northwest from Marina and 105 km from the epicentre. Marina district is situated on the fill created after the 1906 earthquake. This part of the city was constructed in the early 1920's. There are two main types of wood frame houses: 2-storey townhouses with garages on the first level, and 3-4 storey large apartment houses with bottom floor taken up by garages. There is no separation space between buildings.

Many 3-4 storey apartment houses situated at the street corners were badly damaged. There were 2 or 3 spectacular collapses of the entire building when the one or two storeys were completely leveled. The garage floors had acted as a "soft storey" with no lateral resistance. These floors appeared to have no or only limited bracing, or had sheathed walls constructed with boards nailed to posts. Connections between posts and second floor framing were poor and unable to withstand the amount of shift caused by the magnified shaking. This resulted in large deformation or the collapse of one or two storeys as mentioned above. The external stucco, brick or fake stone walls were severely damaged. Many 2-storey townhouses within the blocks also sustained some damage over garage doors and in walls.

Figures B8 and B9 show examples of the "soft storey" effect. A 4-storey apartment building was shifted horizontally by more than 50 cm. Note that the corner bracing is inadequate to prevent the shift in this direction. Another corner building with first storey entirely taken up by garages is presented in Fig. B10. A close-up of the connection between a post and second floor framing is shown in Fig. B11. For corner buildings where more horizontal resistance is provided by sheathed walls, the damage is much smaller (Fig. B12).

Figures B13 and B14 show some cases of damage to 2-storey houses located within the city block. In one case, large windows were destroyed. In general, upper floors sustained little or no structural damage although the entire ground floor of the building shifted.

5.2 Unreinforced Masonry Buildings

Unreinforced masonry buildings built at the turn of this century suffered severe damage. Many of these structures in the older parts of Santa Cruz, Watsonville and Los Gatos were heavily damaged or have partially collapsed (Figs. B15, B16 and B17).

The out-of-plane failures of upper portions of walls and of parapets were common. In some cases the severe shaking on the level of the roof structure resulted in separation of the roof from the walls. The result was not only the collapse of upper portions of walls but also of the roof structure and this inflicted heavy damage to lower floors. An example of damage to an old unreinforced masonry storage building from Oakland near the collapsed Nimitz expressway is presented in Figs. B18 and B19.

Upgraded unreinforced masonry buildings performed well. The upgraded institutional stone masonry buildings at Stanford University in Palo Alto also performed well, in contrast with unreinforced masonry and old style reinforced concrete buildings that suffered damage estimated at $160 million.

5.3 High-rise Buildings

The high-rise buildings in downtown San Francisco and Oakland rode out the earthquake without serious damage to the structural frame or the functionality of the buildings. However, problems were encountered with elevator counter weights jumping their guide rails, and with breakage of glass panes that showered debris onto the street.

It should be noted, however, that the ground motion experienced by these buildings is about one half to one quarter those of the "design earthquake" for that location.

6. PERFORMANCE OF SERVICES

Sections 6.1 to 6.4 and portions of 6.5, all within quotations, were obtained from ASCE News, December 1989, Vol. 14, No. 12, p. 15.

6.1 Transportation Systems

"Many of the transportation systems in the five-county area that were most severely impacted by the earthquake were affected in a significant fashion (with the highway system suffering the most damage). The collapse of more than a mile of elevated roadway of Interstate 880 - the Cypress St. viaduct - was the largest contributor to the earthquake death toll. Also, the loss of a 50 ft span on the upper deck of the San Francisco-Oakland Bay Bridge (and subsequent damage to the lower deck) caused major transportation problems; of the 1,500 highway bridges in the area, three had one or more spans that collapsed. Ten others were closed due to structural damage; 10 required shoring so they could be safely used; and 73 others suffered less severe damage. Throughout the entire region, subsidence of some of the bridge approaches next to abutments were filled with asphalt in order to reduce large bumps in the road surface."

"Damage to the control tower at the San Francisco international airport closed the facility for 13 hours, and liquefaction and settling also forced a runway closing at the Oakland airport. Damage to the roadbed of Caltrain temporarily disrupted service between San Jose and San Francisco. But the BART rapid transit system performed well with only temporary disruptions of service."

6.2 Water and Sewage Systems

"These were damaged in a number of communities from the epicentral region around Santa Cruz to San Francisco. Most disruptions to water supplies could be attributed to other causes. Assessment of damage to sewage collection systems is more difficult and the extent of damage has not been determined. Typically, sewage systems are more seismically vulnerable than water systems. There was extensive damage to water lines from ground deformations, however. For instance, in San Francisco there were 72 significant pipe failures in the heavily affected Marina District and 25 breaks outside that area (with 10 of these concentrated in the Market Street south area). The 12-in. high-pressure (fire fighting) and regular water lines did not break in the Marina. But a break in a 12-in. high-pressure line south of Market, where there was significant liquefaction, quickly depleted a 750,000-gal tank used for fire fighting. In Hollister, there were over 100 broken water mains and over 60 mains broke in Santa Cruz. The failure of a bridge near the city also took out water and sewage lines. In Santa Clara County one of two 66-in. raw water lines failed where it crosses the San Andreas fault. In Los Gatos, a 30-in. raw water line from the Lexington Reservoir failed. The East Bay Municipal District lost a 60-in. concrete-covered, spiral-welded steel line due to the failure of welds. It was repaired within three days after the earthquake. In addition, there were over 140 broken mains."

6.3 Power Systems

"Initial power outages affected about 1.4 million customers. Within 48 hrs, though, service to all but 26,000 of those had been restored. The most severe damage occurred to substations, primarily ceramic members of circuit breakers and oil leaks to transformers. Major damage to two key substations in San Jose and San Mateo contributed to an interruption of service in San Francisco and in areas south of San Jose. Damage to the 500-kV switchyard at the Metcalf substation limited the ability to serve points up the peninsula. The 500 kV switchyard at Moss Landing was also severely damaged, interrupting service in Santa Cruz and Watsonville. At least one distribution station in the epicentral area also had its transformers damaged. A key element to restoring service was replacement of damaged equipment. New equipment was flown in from the east coast with Air Force help and some equipment came from utilities in southern California through mutual-aid agreements."

6.4 Gas System

"There was little damage to gas transmission and large distribution lines, with only three failures reported. There were leaks in a 20-in semi-high pressure welded steel distribution line in Oakland, a 12-in. line in Hollister and an 8-in. line in Santa Cruz. In the Marina, about 10 mi of gas lines will need to be replaced at an estimated cost of $20 million; it is expected to take about two months." The gas lines in the Marina district were made of iron and were very brittle. New gas lines were being installed in the same area using flexible plastic pipes according to ASTM 2513 specifications.

6.5 Communications Systems

As in most earthquakes, an increase in telephone traffic in the hours immediately after the event overloaded the system so that there were long delays in getting dial tones on nonpriority lines. All telephone systems are designed to accommodate reasonable peak loads; thus, overloads after an earthquake are to be expected. This time, though, in general, calls could be made within the same area code in most areas if there were dialed several times. Service announcements on the radio right after the earthquake requested that only emergency calls be made; this probably contributed to the system's overall good performance.

6.6 Elevators

California has a special elevator code for use in tall buildings in earthquake zones. The performance of many elevators built according to this code, however, was poor. Many problems were encountered, the most common one being that the counter weight jumped off the guide rail which rendered the elevator unusable. It appears that the code needs revising.

6.7 Automatic Shutoff Valve for Gas Supply

Automatic shutoff valves for gas supply exist in California but they are very unpopular for the following reasons:

(1) The automatic shutoff valve is triggered upon vibration. It is, therefore, very vulnerable to vandalism. Simply kicking the valve by children will shut off the gas supply. Therefore, property owners are reluctant to install it.

(2) Once shut off, the valve cannot be turned on again until it is carefully inspected by qualified gas company personnel. This creates a great deal of inconvenience.

(3) During a small earthquake near Los Angeles in 1987, a public announcement was made through television to urge residents to shut off their gas valves. Up to 80,000 buildings complied and the gas company was subsequently swamped with calls to reopen the valves. Some had to wait for two weeks for their turn. This experience definitely discouraged people from installing the automatic shutoff valves.

6.8 Summary of Damage Distribution

A preliminary overview of the distribution of damage to buildings in the various counties of the San Francisco region is shown in Table 1, along with the prevailant level of ground acceleration in the major built-up areas. The county boundaries are shown in Fig. B1. For comparison purposes with the design earthquake effects for Vancouver, Santa Cruz County should not be included since this represents the epicentral region with accelerations that substantially exceed the expected acceleration range for the Vancouver "design earthquake".

Table 1: Preliminary Data on Damage Distribution
(adapted from Ref. 8)

County	Fatalities	Injuries	Damage ($Billions)	Buildings Condemned	Buildings Damaged	Peak Accel., %g*
Alameda (Oakland)	39	349	1.5	29	3,411	10-15
Monterey	1	None	0.05-0.1	45	144	(5-10)
Santa Clara	5	>650	0.65	>71	104,884	20-40
Santa Cruz	6	NA	1.0	580	3,290	40-60
San Francisco	13	NA	2.0	>350	NA	10-20

NA: Not available
*: dominant level in major population centres; ( ) estimated.

The number of buildings immediately condemned is seen to be around 500, excluding Santa Cruz. The following is quoted from Ref. (8):

> It is currently estimated by the Federal Emergency Management Agency (FEMA), the California Office of Emergency Services and others that more than 105,000 homes, 320 apartment buildings, and 1,345 businesses have been damaged by the earthquake. It is expected that more than 1,000 structures will have to be condemned and demolished. In total, more than 7,362 people have been displaced from their homes by the earthquake.
>
> At least 64 fatalities have resulted from the earthquake, 38 of these from the collapse of the Cypress viaduct alone, and 79 people remain missing following the earthquake. More than 2,400 individuals suffered injuries requiring medical treat-

ment. While these numbers are tragic, it must be recognized that injuries would likely have been much higher if it were not for the fact that many people had gone home from work early on the day of the earthquake to watch the "World Series" of baseball.

7. NOTES ON EMERGENCY PREPAREDNESS

California has made extensive preparations for the effects of earthquakes, and these preparations have paid off in dealing with this disaster. Most California cities have annual drills for earthquake emergency. The drills are costly and inconvenient but they demonstrated their value. Shortly after the earthquake, control centres were set up at the major disaster areas and were staffed by police, firefighters, rescue workers, building inspectors and authorized volunteers. As one example, and as part of the emergency plan, volunteers from as far as Los Angeles were on their way to the San Francisco Bay area within minutes after the earthquake.

In the epicentral area, tent shelters were erected in public parks and food was provided by the Red Cross. Transportable trailer-mounted washrooms were provided for people staying in temporary shelters. Damaged buildings in affected areas were quickly inspected by structural engineers who had previously been trained in earthquake damage assessment. Buildings were categorized into 3 groups: safe, unsafe, and limited access. Access was completely denied to "unsafe" buildings; entry into buildings declared "limited access" was permitted under supervision and for short periods only.

Communication systems performed well. The use of cellular phones was singled out as the best performer at the control centres located in specific disaster areas. CB radios were completely jammed because of the overwhelming usage after the earthquake. Other telephone lines were in operation except those that went through sophisticated private switching units. Some switching units failed because of power outage.

8. BASIS FOR APPLYING SAN FRANCISCO EXPERIENCE TO VANCOUVER

To arrive at a rational basis for comparing the effects of the San Francisco area earthquake of 1989 with seismic damage predictions for the Vancouver area, a comparison of the dominant parameters that affect major damage to structures needs to be undertaken. Within the allotted time and resources, such a comparison can only be undertaken on a judgemental basis, however.

The main parameters that affect the damage comparison are:

- Earthquake characteristics (magnitude, depth and type of rupture, duration, frequency content)
- Location of earthquake, distance and direction from epicentre
- Geology and soil conditions
- Type of construction
- Level of earthquake resistant design in use when buildings were constructed.

These will now be discussed in more detail.

8.1 Earthquake Characteristics

The Magnitude 7.1 Loma Prieta earthquake generated ground motions consisting of relatively low frequencies (judged to be mainly between 1 to 3 Hz horizontally, and 2 to 6 Hz vertically) and duration of shaking of about 10-15 seconds. These are typical values for moderate earthquakes that occur on the west coast of California. By reasonable extrapolation, a similar type of earthquake can be expected for Vancouver, with the epicentre within about 80-100 km of the city. Earthquakes with a Magnitude 6 and above, with epicentres of about 30-50 km from the city would have similar effects, although the duration might be somewhat less. On the other hand, earthquakes larger than Magnitude 7.0 at distances of 150-200 km could be expected to produce similar ground motion amplitudes but with longer duration. This progression of magnitudes then leads to the "large earthquake" or "subduction earthquake", with possible magnitudes up to 9.3 and duration in the minutes.

Frequency content is a function of the rupture mechanism, magnitude, distance and geologic features in the affected area. It can reasonably be assumed that frequency content in a future earthquake near Vancouver is not significantly different from that of the San Francisco area ground motion. A notable exception is the presence of soft soil deposits, where the lower frequencies can be amplified. This has also occurred in San Francisco at soft soil deposits.

8.2 Codes and Standards

Two major types of construction can be recognized: a) engineered construction and b) residential "non-engineered" construction.

8.2.1 Engineered Construction (Part 4, NBC)

Engineered construction follows applicable building codes as a minimum, but these standards are often exceeded for special structures such as some tall buildings or major bridges. Most buildings in the San Francisco Area would be designed to a Zone 4 requirement in the 1985 Uniform Building Code (UBC). In the Vancouver area the requirements in the National Building Code of Canada (NBC) correspond to those of a velocity and acceleration zone $Z_a=Z_v= 4$ with $v = 0.20$.

For the San Francisco area, the 1985 UBC design base shear V for low level buildings is (using its own notation):

$$V_{UBC} = Z\,I\,K\,C\,S\,W$$
$$= (1.0)\,(1.0)\,(1.0)\,(0.12)\,(1.0)\,W$$
$$V_{UBC} = 0.12W$$

where W = weight of building.

For a comparable building in Vancouver, the 1985 NBC prescribes for base shear (using its own notation):

$V_{NBC} = vS\ K\ I\ F\ W$
$= (0.20)\ (1.0)\ (1.0)\ (1.0)\ (0.44)\ W$
$V_{NBC} = 0.088W$

For tall buildings (example period T = 2s), $V_{UBC} = 0.047W$ and $V_{NBC} = 0.031W$. Since both codes utilize a load factor of about 1.5, it can be seen that the ratio of design forces for Vancouver to those of San Francisco is about 2/3. Thus Vancouver would correspond approximately to a Zone 3 requirement in the UBC, one UBC seismic zone lower than that of San Francisco.

8.2.2 Residential Construction (Part 9 of NBC)

Non-engineered buildings comprise single family houses and multi-unit dwellings up to and including 3 storeys in height and of a limited size. Specific aspects are treated subsequently.

Table 2 compares California and Canadian earthquake requirements for residential construction governed by Part 9 of the NBC. The California requirements are contained in the Uniform Building Code (UBC). Table 2 shows UBC and NBC are similar except some earthquake requirements in the UBC are missing from the NBC. Where requirements exist in both codes they are essentially identical in content.

The experience of the Loma Prieta earthquake indicates that the most serious deficiency in Part 9 of the NBC is the lack of any requirements for wall bracing in wood frame construction. Ground storeys of 2 or 3 storey residential buildings containing large openings may collapse laterally, with serious consequences. This may be important for certain townhouse and apartment configurations. The UBC requirements for wall bracing are indicated in Fig. 7.

Other deficiencies in Part 9 of the NBC include the need for end tieing of beams over supports (apparently some floor failures occurred related to this deficiency) and anchorage of masonry chimneys to the roof and floors. Collapses due to these deficiencies have occurred in this and previous earthquakes.

Lateral collapse of foundation walls weak in racking resistance (such as cripple-stud walls) was also a serious failure mode near the epicentre. This is covered by the NBC Part 4 lateral force requirements via Clauses 9.15.1.5 (for wood construction) and 9.4.1.1 (for construction not specified in Part 9). Many people may not be aware of this, however. This may therefore indicate a need for a brochure on earthquake resistant construction practices.

Practically all the serious structural failures that occurred to residential construction were due to deficiencies that are prohibited by recent codes. Although the earthquake intensity was less than the design earthquake except near the epicentre, the experience indicates that the present UBC requirements are satisfactory. An exception to this is that the veneer anchor ties specified in 3006(d)1 for the UBC were not sufficient. Since Part 9 has a similar requirement, we should find out the detailed reasons for the failures and monitor any proposed changes that will result to the UBC.

The main problem in Canada, however, concerns the safety of existing buildings with serious deficiencies, particularly 3 storey wood frame complexes with weak ground storeys on soft ground. Other hazards include the lack of lateral support of masonry whose collapse is life

threatening. The seismic evaluation and upgrading of existing residential construction therefore requires attention.

Table 2 Comparisons of Earthquake Code Requirements for Residential Construction

Requirement	1985 UBC	1985 NBC Part 9
1. Wall Bracing (in-plane)	2517(g)3	Not covered except for post and beam construction Part 4 via 9.24.1.5
2. Cripple stud Foundation Walls	2517(g)4	Part 4 via 9.15.1.5
3. Anchorage to Foundations	2907(f)	9.23.6
4. Beam Splice Ties over Supports	2517(c)	not covered
5. Lateral Support of Masonry Walls	2407(e)	9.20.10 and 11
6. Anchorage of Masonry Veneer	3006	9.20.9.9
7. Reinforcing of Masonry	2407(h)4B	9.20.17
8. Anchorage and Reinforcing of Masonry Chimneys	3704(c)	not covered
9. Stability of Masonry Parapets	2312 Table 23-J	9.20.6.7

8.3 Level of Earthquake Resistant Design

8.3.1 Engineered Construction

The level of earthquake resistant design that was employed when the buildings were constructed also plays a role in comparing damage potential. As was pointed out above, the seismic requirements for engineered construction are lower in Vancouver than in San Francisco. Therefore the same earthquake would be expected to produce more damage in the area having the lower requirements, i.e. the greater Vancouver area.

8.3.2 Residential Construction

Nominal lateral resistance in the UBC is achieved by specifying minimum percentages of shear panels in the walls. Since no such requirement is contained in the NBC (Part 9) it can be concluded that on the average the lateral resistance of houses in Vancouver is likely to be slightly less than those in the San Francisco area, thus making these buildings somewhat more vulnerable to comparable size earthquakes. The level of awareness among builders of potential earthquake hazard is also likely to be somewhat higher in California than in British Columbia, again pointing to a possible lower level of overall seismic resistance for houses on the B.C. coast. It should be pointed out, however, that the inherent lateral resistance in most houses is quite high and therefore the overall reduction in seismic resistance should be marginal, estimated at about 5-10 % averaged over a large number of buildings.

9. DAMAGE ASSESSMENT FOR THE VANCOUVER AREA

Extension of the San Francisco area earthquake to the ground motions corresponding to the design earthquake for Vancouver requires a number of assumptions and extrapolations. As a rough approximation, the peak ground accelerations recorded from a particular earthquake can be compared on a par with the specified design acceleration in the NBC. On that basis, the specified acceleration for Vancouver being 20%g, the San Francisco region was subjected to ground motions ranging from about 3 times that value (64%) in the epicentral area, down to about one half (10%g) in Oakland and parts of the city of San Francisco. It can be expected that this range would be smaller in the Vancouver area since the epicentre is assumed to be relatively far removed from densely populated regions. Thus it is estimated that a range from 30% to 10%g would apply for Vancouver, i.e. straddling the "design" acceleration of 20%g. Based on this argument it may thus be concluded that on average the San Francisco area earthquake outside the epicentral region corresponds quite closely to the NBC design earthquake for the Vancouver area.

9.1 Damage Estimate for the Vancouver Area

In a previous study (Ref. 11) an assessment has been made of the damage that could be expected for Vancouver at two levels of earthquakes: a) an earthquake corresponding to the NBC "design earthquake" of 20%g, and b) a major subduction earthquake with an assumed nominal ground acceleration of 50%g. The calibration that is carried out here with the San Francisco area earthquake corresponds to the effects of an NBC design level earthquake.

The estimates of major damage in the greater Vancouver area are greater than what was experienced in San Francisco for the following reasons: a) the design level for earthquake resistance (NBC Part 4) is lower than in San Francisco, b) the seismic requirements for residential construction (NBC Part 9) are less stringent, c) the extent of soft soils in populated areas is larger than in San Francisco and d) the recorded ground motions in the most populated areas, San Francisco and Oakland, were from one half to two thirds the design earthquake for Vancouver.

More problems with soil amplification and liquefaction can be expected in Vancouver, as was already pointed out in the previous IRC study, Ref. 11. It is noteworthy that problems with foundation failures were encountered in areas of San Francisco that had a ground acceleration on firm ground of about 10%g. This can be seen by comparing the plot of soil problems encountered, Fig. 5, with the contour map of recorded ground accelerations shown in Fig. 3. The predictions of potential problems with soft soil have thus been re-affirmed in the San Francisco area earthquake. The soft soils are seen as a likely cause of major damage in the Vancouver area including the Fraser Delta, the False Creek area, and other deposits of soft soils and manmade fills.

As a result of the site visits to the San Francisco area, starting 8 days after the event, a re-assessment has been made of the earlier prediction in Ref. 11. This has resulted in some small changes in the estimated damage figures for some categories and re-confirmed in the opinion of the writers the reasonableness of the other original estimates.

The following are reasons for the changes to the original estimates:

1. For low and medium rise residential buildings, the original estimate of 5-10% damage was thought to have been too high, based on the San Francisco experience. These types of buildings have fared no worse than the single family houses and therefore a similar estimate seems appropriate.

2. Communication systems have performed relatively well in San Francisco, not the least of the reasons being careful planning, drills, and attention to design. It is quite certain that the same level of attention has not been expended in Vancouver, but it was nevertheless felt that the original estimate was too high.

The San Francisco area earthquake was not of sufficient magnitude to provide information to alter the predictions for the major subduction earthquake. Too many uncertainties exist in the nature of the postulated ground motion and in the anticipated structural and soil behaviour to permit an expression of more certainty.

Table 2: Revised Summary of Estimated Major Structural Damage
Original Table from Ref. 11; changes as a result of the present investigation are indicated in bold letters with original figures placed in parentheses

	Design Earthquake (NBCC 1985)	Major Subduction Earthquake
Probability of Occurrence: (per annum) (return period, years) Peak Ground Acceleration:	0.0021 475 0.20 g	600-1000 0.50 g
Type of Building or Service	Estimated Loss Ratio, %	Estimated Loss Ratio, %
Single family houses of wood frame construction	2-5	10-30
Unreinforced masonry	20-50	50-100
Low and medium rise residential and office	(5-10) **2-5**	20-30
High-rise residential	5-10	10-20
Schools and hospitals: old construction < 1940 (not strengthened) newer construction **and strengthened old construction**	10-30 2-5	30-60 10-20
Gas and water supply, sewers	5-10	40-60
Electricity	5-10	20-50
Communication systems	(10-20) **5-10**	20-40
Transportation routes (bridges)	5-10	20-30
Harbour facilities	5-20	40-50
Airport structures runways	2-5 5-20	10-20 40-70

10. SUMMARY AND CONCLUSIONS

The Loma Prieta earthquake that hit the San Francisco area on October 17, 1989 caused $10 billion (U.S.) damage and over 60 deaths. Buildings built in the last 20-30 years and located on firm ground performed well, while older houses and those located on soft deposits suffered major

damage and often collapse. Soft soil deposits have again demonstrated their potential for amplification of shaking and loss of bearing capacity due to liquefaction, with subsequent risk to structural integrity and safety to occupants.

The conditions found in the San Francisco area were extrapolated to what might be expected in a "design earthquake" in the greater Vancouver area. The damage predictions in the previous CMHC study were largely re-affirmed; small reductions in loss ratio were judged appropriate for low and medium rise residential and office buildings, and for communication systems.

A comparison between the 1985 Uniform Building Code and the National Building Code of Canada shows that the requirements for Residential Construction, Part 9, have potential shortcomings concerning lateral bracing, beam splice ties over supports, and anchorage and reinforcing of masonry chimneys.

The experience from the San Francisco area indicates that upgraded buildings performed well. Such upgrading should continue to be pursued in the Vancouver area after evaluating seismic capacity and identifying any shortcomings. Area mapping of site characteristics (micro-zonation) would prove useful for improved risk evaluation.

The high level of emergency preparedness in the affected San Francisco area provided for effective rescue operations, relief and care for evacuated people and a return to near-normal operating conditions of community within a few days of the earthquake.

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[5] R. Maley, A. Acosta, F. Ellis, E. Etheredge, L. Foote, D. Johnson, R. Porcelle, M. Salsman and J. Switzer - "U.S. Geological Survey Strong-Motion Records from the Northern California (Loma Prieta) Earthquake of October 17, 1989" - U.S. Geological Survey Open-File Report 89-568, October 1989.

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[11] Jablonski, A.M., Allen, D.E., Law, K.T., and Rainer, J.H., "Assessment of Earthquake Effects on Residential Buildings and Services in the Greater Vancouver Area", Client Report No. CR-5810.1 to CMHC, Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario, 8 Dec. 1988, 34 p.

[12] Borcherdt, R.D., Joyner, W.B., Warrick, R.E. and Gibbs, J.F., "Response of Local Geologic Units to Ground Shaking" in Studies for Seismic Zonation of the San Francisco Bay Region, U.S. Geological Survey Professional paper 941-A, 1975.

[13] Bush, V.R., Handbook to the Uniform Building Code, International Conference of Building Officials, Whittier, CA, 1988.

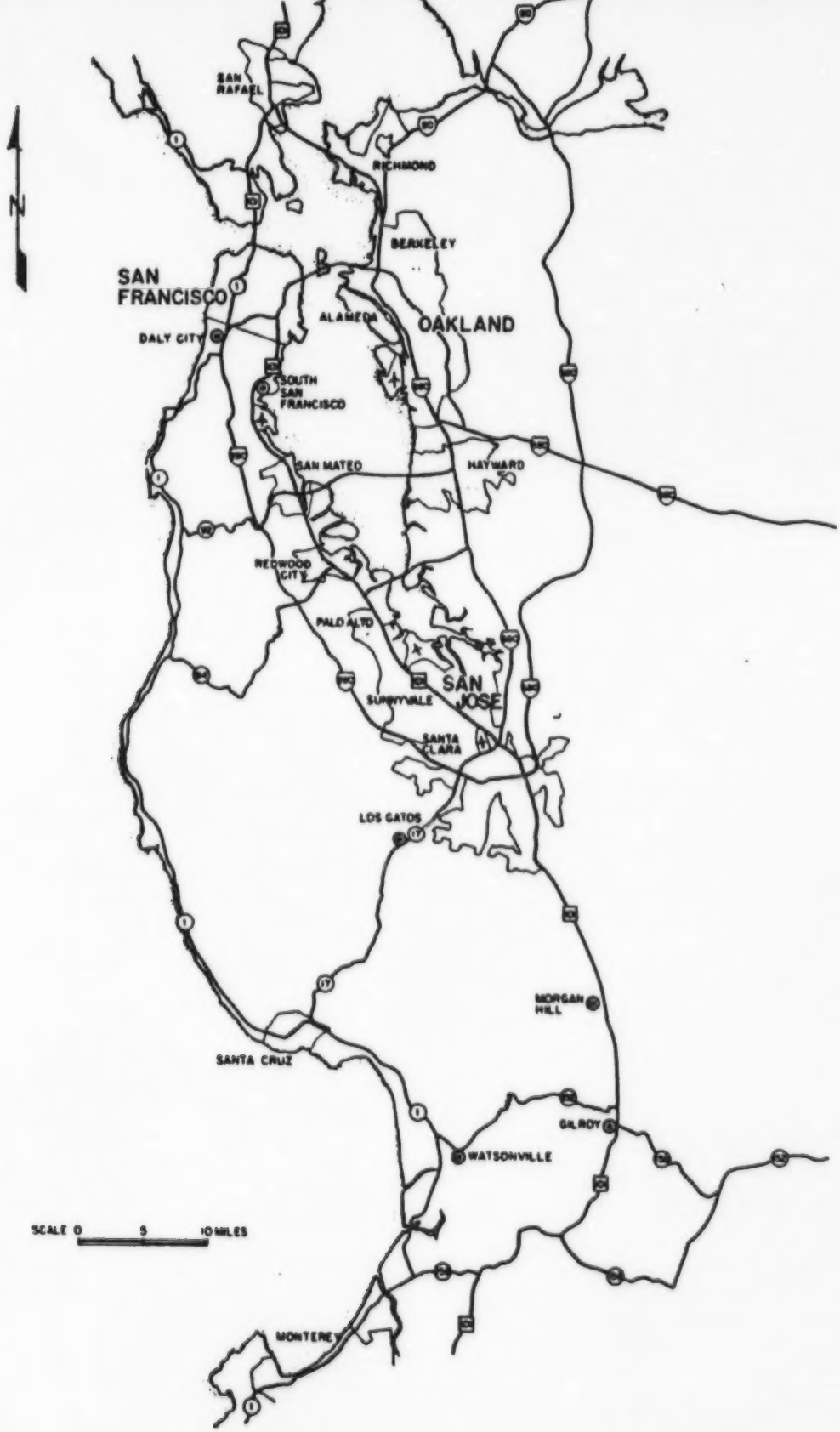

Fig. 1: Skeleton map of San Francisco Bay Area (from Ref. 8)

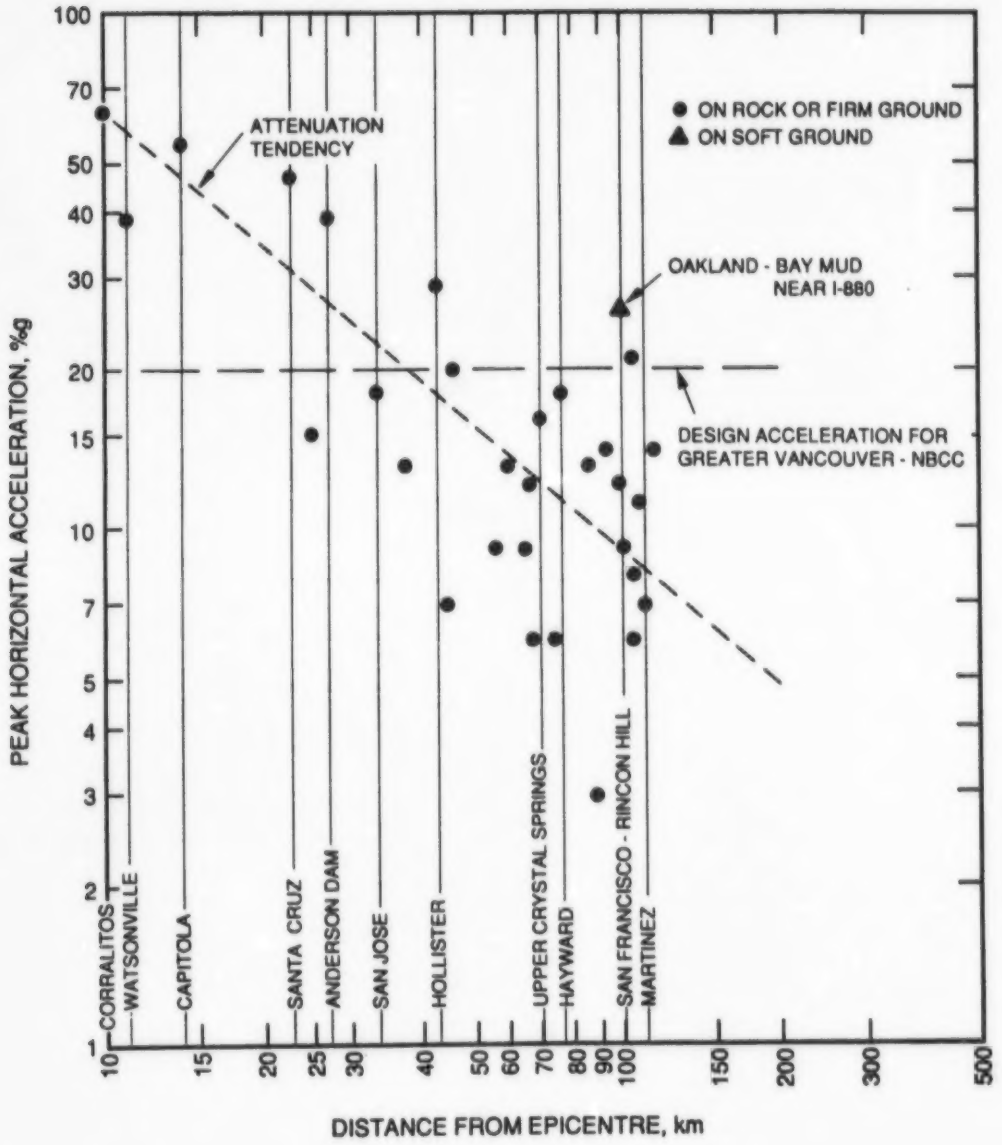

Fig. 2: Measured Peak Horizontal Acceleration vs Epicentral Distance, Loma Prieta Earthquake

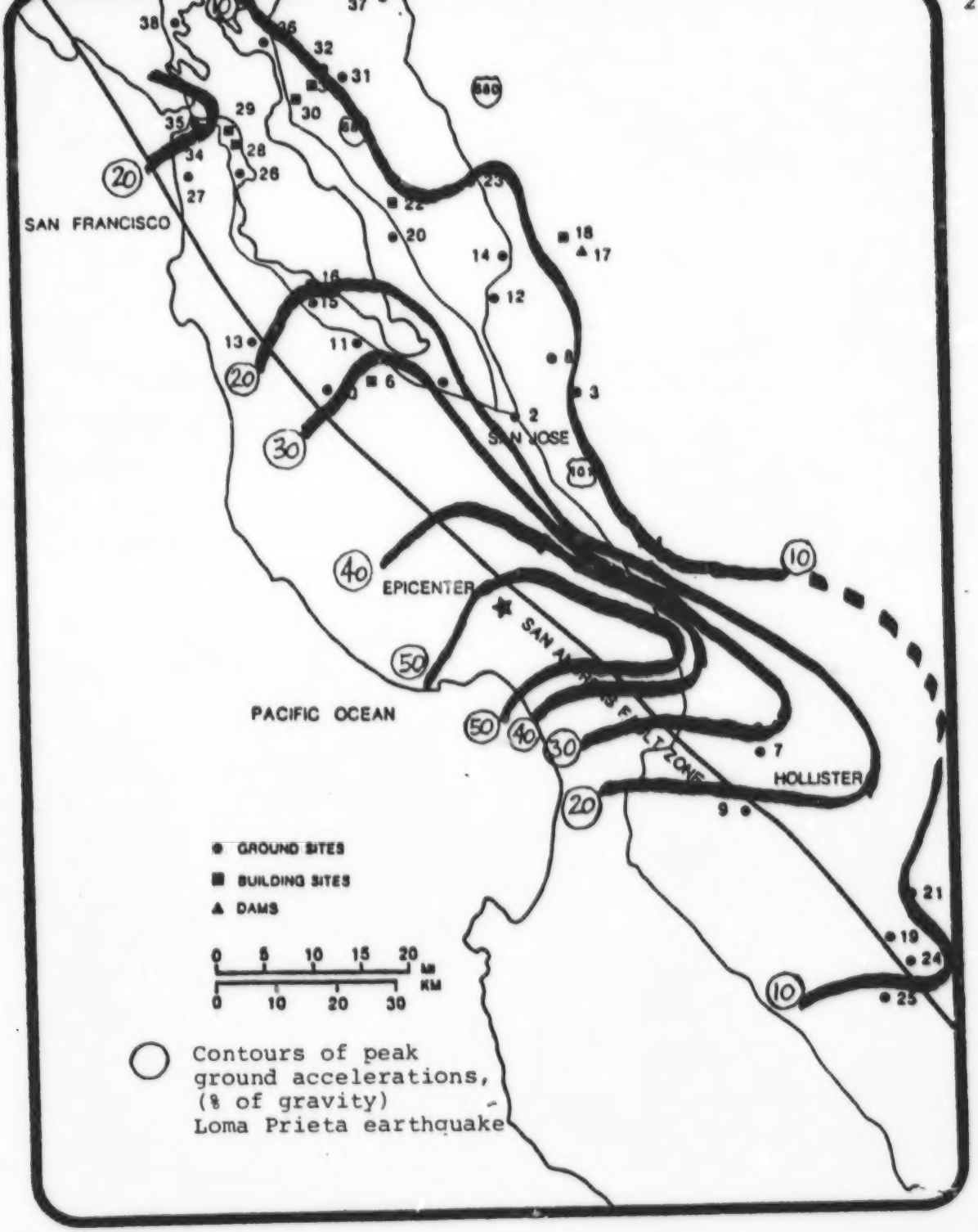

Fig. 3: Contour map of recorded peak ground accelerations in the San Francisco Bay Area, Loma Prieta earthquake

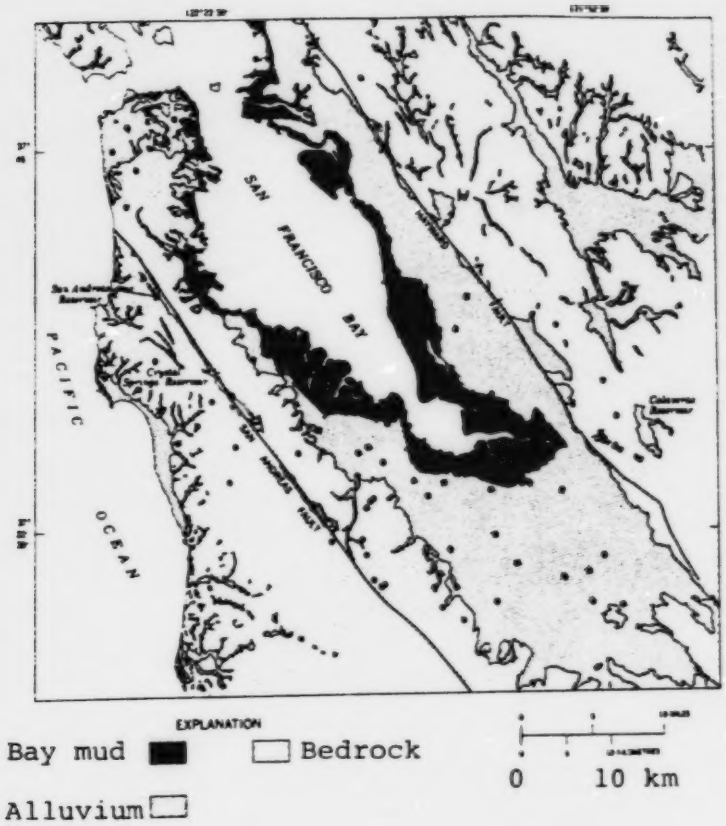

Fig. 4: Generalized surficial deposits in San Francisco Bay Bay Area (after Borchardt et al, 1975, Ref. 12)

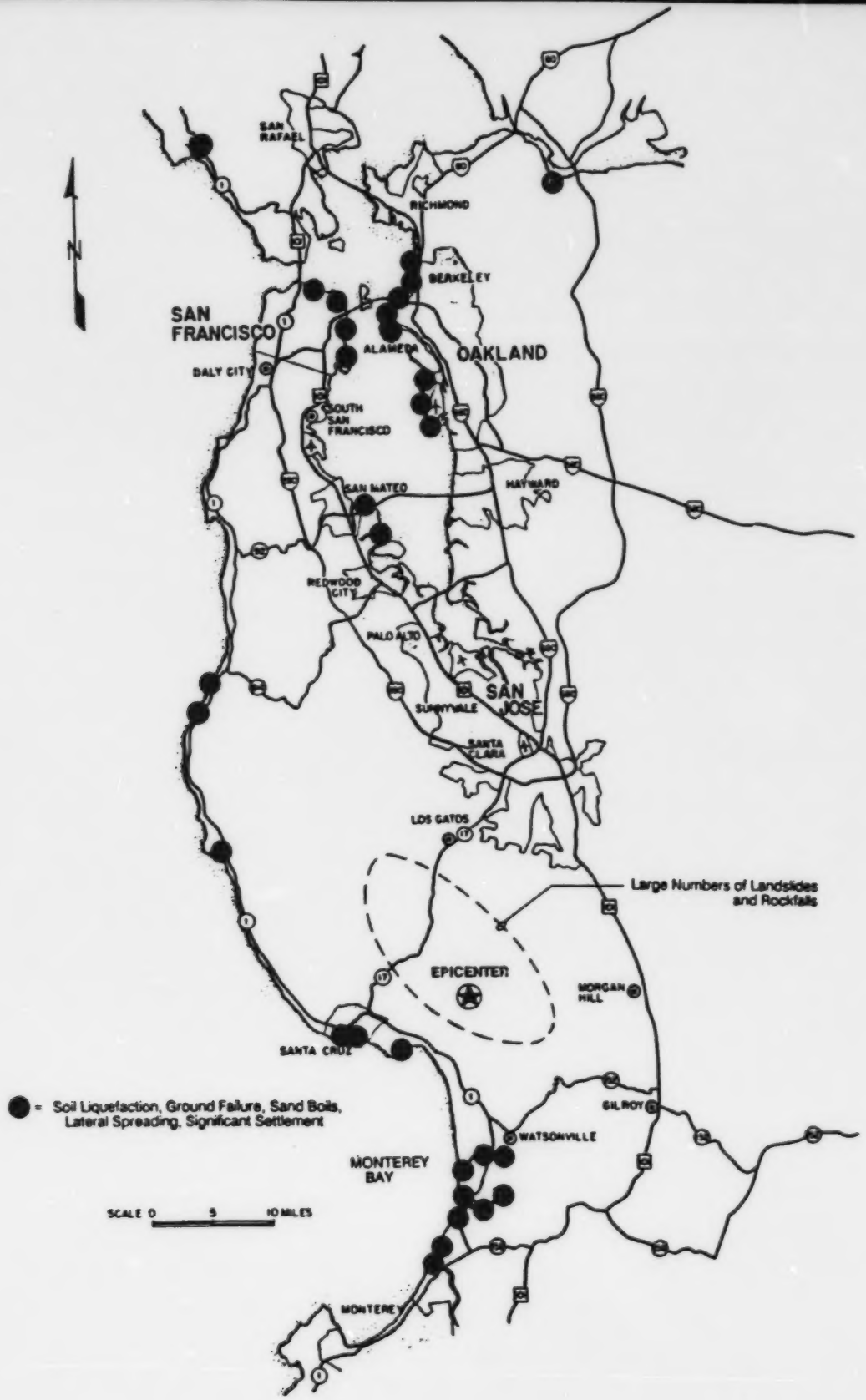

Fig. 5: Map of San Francisco Area showing Location of Soil Failures (Ref. 8)

Section 2517 (g) 4
CRIPPLE WALLS

ADDITION

Cripple walls having stud height of 14 inches or less may be braced with plywood sheathing nailed to the top plate, studs and sill. All studs less than 8" in height will not be accepted and Must be solid wood members.

NOTE:

All new foundations located within the 100 year flood zone must meet minimum of 1 foot above the flood plain requirement. Finish floor elevation must be verified with Public Works.

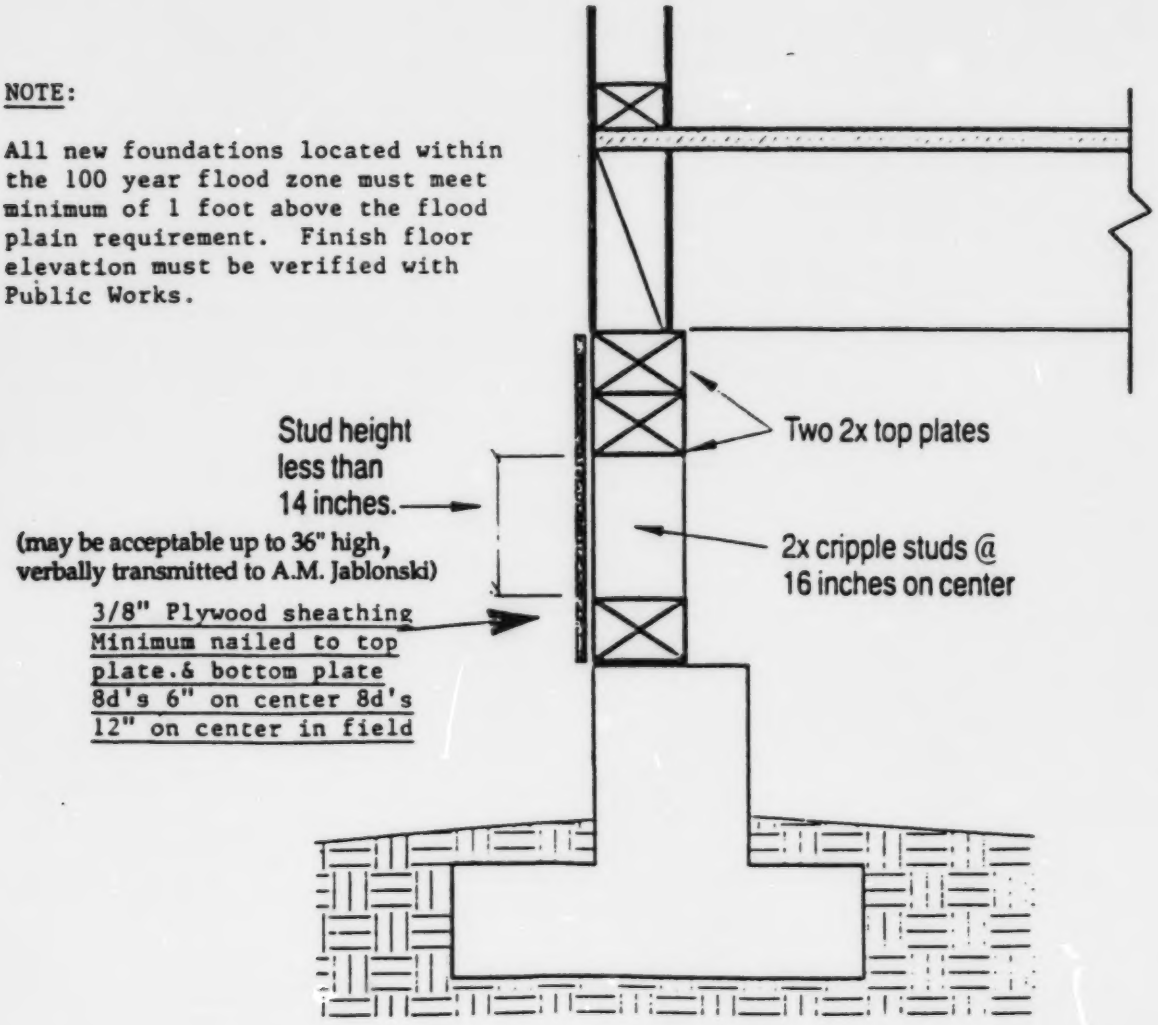

Fig. 6: Specifications for cripple walls, Earthquake requirements, City of Watsonville, CA

See Section 2517 (g) 3 1985 UBC for full description of acceptable bracing:

A. 1 x 4 diagonal brace
B. Solid diagonal sheathing
C. Plywood sheathing
D. Fiberboard sheathing
E. Gypsum board
F. Particleboard wall sheathing
G. Portland cement plaster
H. Hardboard panel siding

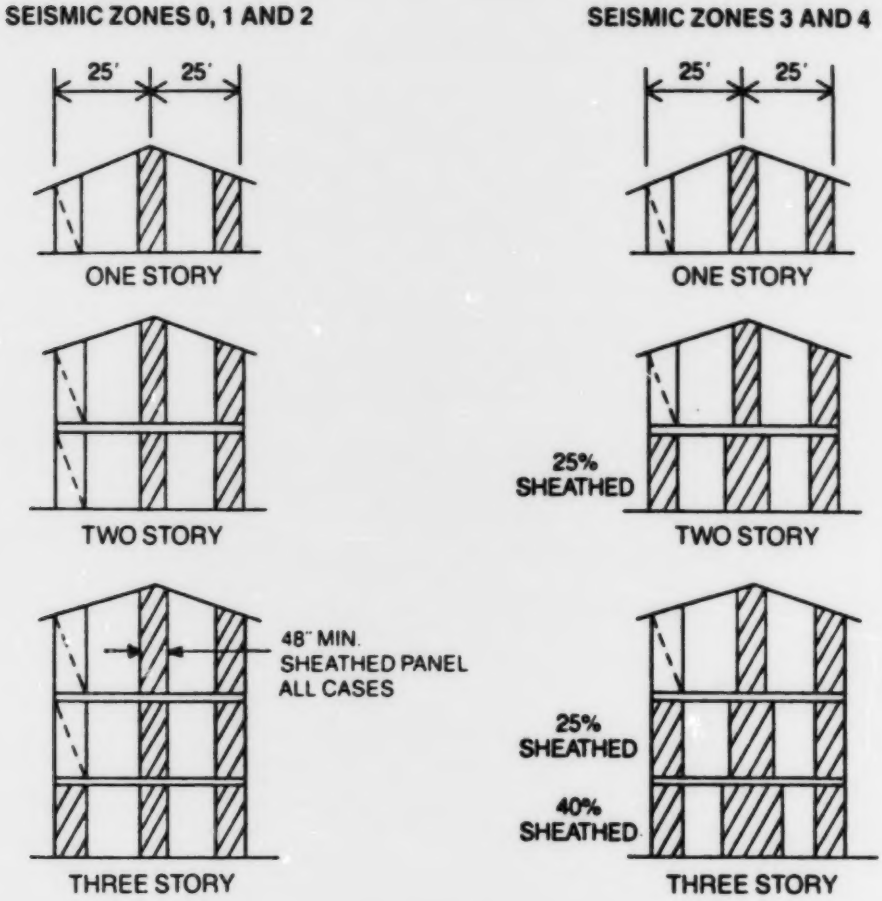

Fig. 7: Wall Bracing Specified in 1985 Uniform Building Code (UBC) for Residential Construction (adapted from Ref. 13)

APPENDIX A

Strong-Motion Seismograph Records

California Strong Motion Instrumentation Program (CSMIP) Network [Refs. 6,7]

Strong motion accelerographs in at least 73 CSMIP network stations were triggered during the Loma Prieta earthquake. They included both ground-response stations and the structure-response records. The closest accelerographs were located in Santa Cruz and in Watsonville and they recorded relatively highest horizontal and vertical peak accelerations: Santa Cruz - 0.64g H, 0.47g V; Watsonville - 0.33g H, 0.66g V. They showed over 10 seconds of very strong shaking and also indicated a very high amplitude vertical motion. The records from San Francisco stations showed large variations depending on the type of soil deposits. At Telegraph Hill and Rincon Hill - two stations in the eastern part of San Francisco - indicated relatively low acceleration: 0.03 H and 0.09 g V. The station at Presidio, about 1.5 miles southwest of the heavily damaged Marine district recorded 0.21g H and 0.06g V, while the station at Pacific Heights situated on stiffer ground only 0.06g H and 0.03gV.

Several structures were instrumented in the CSMIP network. Among them was the station at Lexington Dam located 26 km from the epicenter (0.45g H and 0.15g V measured at abutment) and stations in the city of Oakland in the Lake Merrit district near the collapsed section of the I-880 freeway with 0.26g H range and0.16g V.

U.S. Geological Survey (USGS) Network [Ref. 5]

Strong motion data was also collected from the USGS network. It included 38 stations (21 ground stations (13 large buildings, 5 hospitals, 2 dams and 2 bridge abutments). The closest USGS station was located at Anderson Dam, east of Morgan Hill at a distance of 27 km from the epicentre. The peak accelerations at the downstream located accelerograph reached 0.26g. In Hollister, approximately 45 km southeast of the epicenter, two accelerographs recorded relatively high amplitudes peak horizontal motions, (0.20 g and 0.29 g). These stations were in the reported direction of the main shock propagation (about 10 km of the San Andrea's fault zone). In the Palo Alto Veterans Administration Hospital (6-storey building) peak accelerations were 0.38 g in the basement and 1.09 g on the roof. Several buildings in downtown San Francisco and on the east side of the Bay were instrumented. The famous Transamarica Building on Montgomery Street in San Francisco (72 channels of acceleration data) reported peak horizontal accelerations 0.10g at the foundation and 0.31g at the 49th floor. A 30-storey structure on Christie Avenue in Emeryville, about 100 km north of the epicentre and less than 2 km north of the collapsed I-880 freeway in Oakland, reported max. peak accelerations of 0.26g of the ground and 0.39g at 31st floor level. The south abutment of the Golden Gate Bridge recorded significant horizontal accelerations, 0.12g in the N-S direction and 0.24g in the E-W direction.

Earthquake Acceleration as a function of Location

Based on the preliminary data collected by the USGS and CSMIP the list of the typical peak horizontal and vertical accelerations measured on rock or on firm ground (except as noted) is presented in Table A1.

TABLE A1

Preliminary measured values of peak ground accelerations from the Loma Prieta Earthquake

Station	Estimated Distance from Epicentre (km)	Peak acceleration, %g	
		Horizontal	Vertical
Corralitos (landslide deposits)	5	0.64	0.47
Watsonville (fill on alluvium)	11	0.39	0.66
Capitola	14	0.54	0.60
Santa Cruz	23	0.47	0.40
San Juan Bautista - 101 Overpass	25	0.15	0.10
Anderson Dam	27	0.39	0.19
San Jose Interchange 101/280/680	34	0.18	0.08
Halls Valley	38	0.13	0.06
Hollister Airport	45	0.29	0.16
Monterey - City Hall	46	0.07	0.03
Palo Alto, VA Hospital, Bldg 2	47	0.38	0.20
Palo Alto - 2-storey Office Bldg	57	0.21	0.09
Fremont - Mission San Jose	60	0.13	0.09
Calaveras Array			
Suriol Fire Station	63	0.10	0.03
Redwood City			
Canada College Campus Bldg	65	0.09	0.04
Foster City			
Livermore, VA Hospital Bldg. 62	67	0.06	0.03
Upper Crystal Springs Res.	70	0.16	0.06
Haywant City Hall	74	0.06	0.03
Haywant Muir School	77	0.18	0.10
Bear Valley Station 10			
Webb Residence	86	0.13	0.05
San Bruno - 6-storey office Bldg	89	0.03	0.02
San Francisco Thornton Hall	03	0.14	0.04
San Francisco 575 Market St.	96	0.11	0.06
Oakland - 2-storey building	99	0.26	0.16
San Francisco - Rincon Hill	102	0.09	0.03
San Francisco - Pacific Heights	104	0.06	0.03
San Francisco - Telegraph Hill	104	0.08	0.03
San Francisco - Presidio	105	0.21	0.06
San Francisco - Cliff House	107	0.11	0.06
Martinez, VA Hospital	109	0.07	0.03
Larkspur, Ferry Terminal	115	0.14	0.06
Menhowlen Court	66	0.12	0.09

APPENDIX B
Maps and Photographs

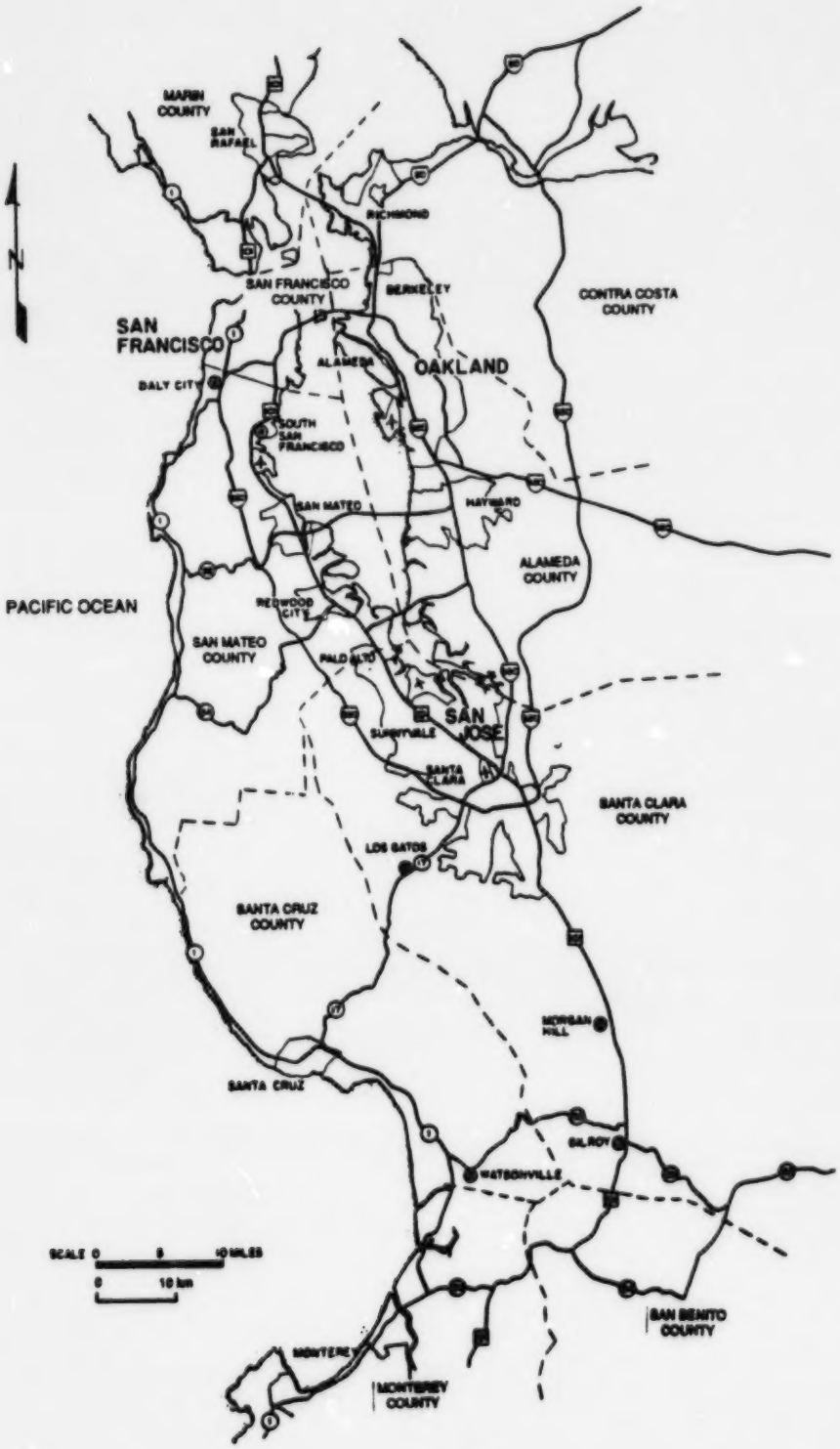

Fig. B1: The geographical areas affected by the Loma Prieta Earthquake

Fig. B2: Old house with cripple wall failure affecting the integrity - 114 Brennan Street in Watsonville

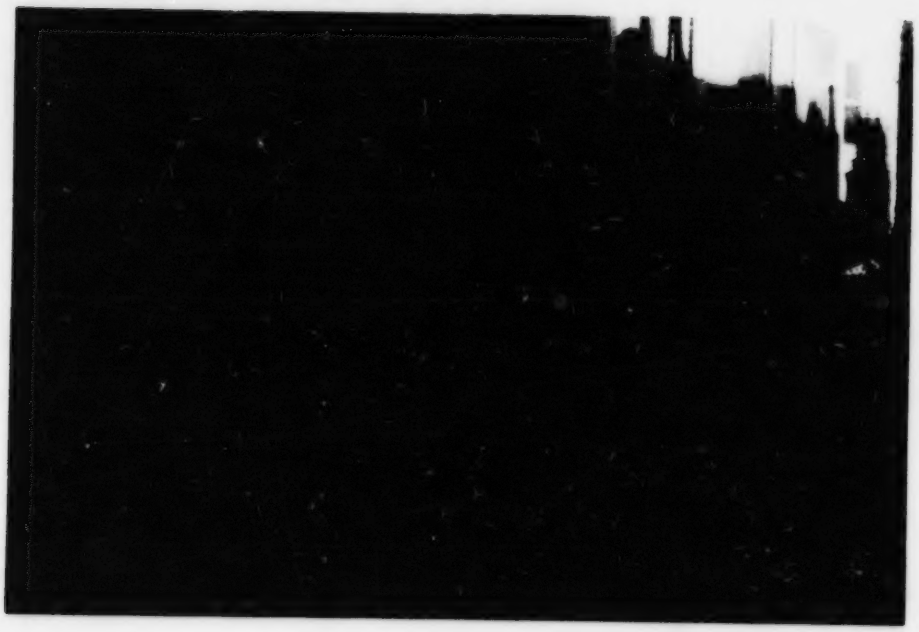

Fig. B3: Close-up of cripple wall failure - 114 Brennan Street in Watsonville

Fig. B4: Complete collapse of cripple wall and destroyed porch partly due to foundation settlement - 130 Brennan Street in Watsonville

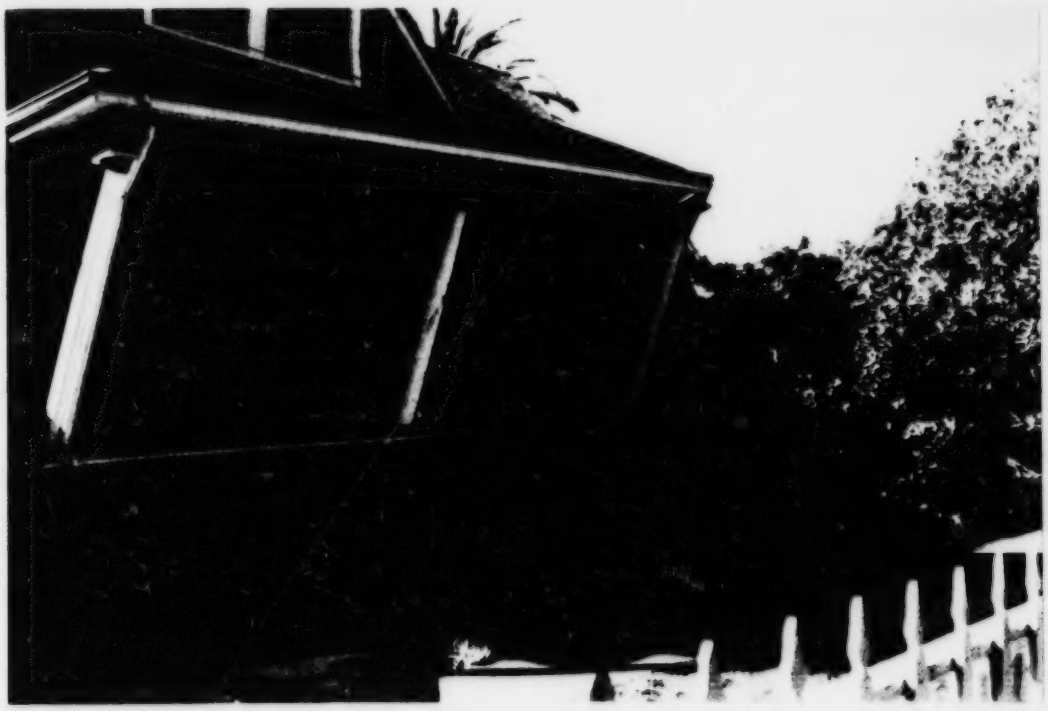

Fig. B5: Collapsed Cripple wall and porch in the residence at Main Street in Los Gatos

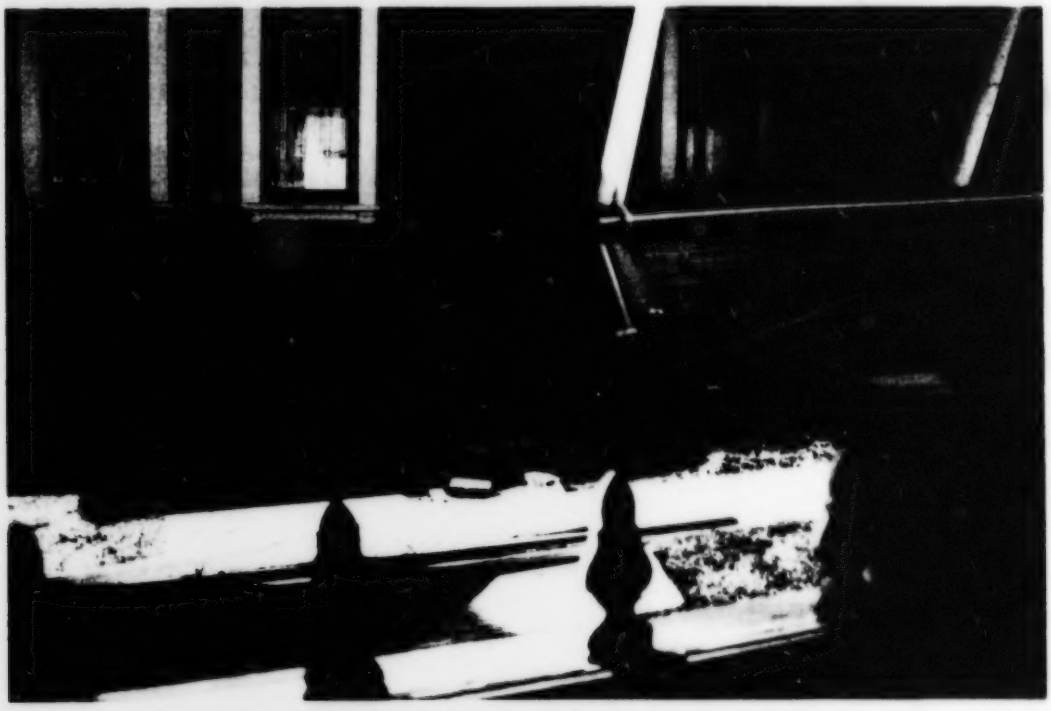

Fig. B6: House was shifted from the foundation by approximately 18' - residence at Main Street in Los Gatos

Fig. B7: Partially collapsed porch in residence at Main Street in Los Gatos

Fig. B8: Damage to a 4-storey wood frame apartment building at the corner of beach and Broderick Streets, Marina District, San Francisco

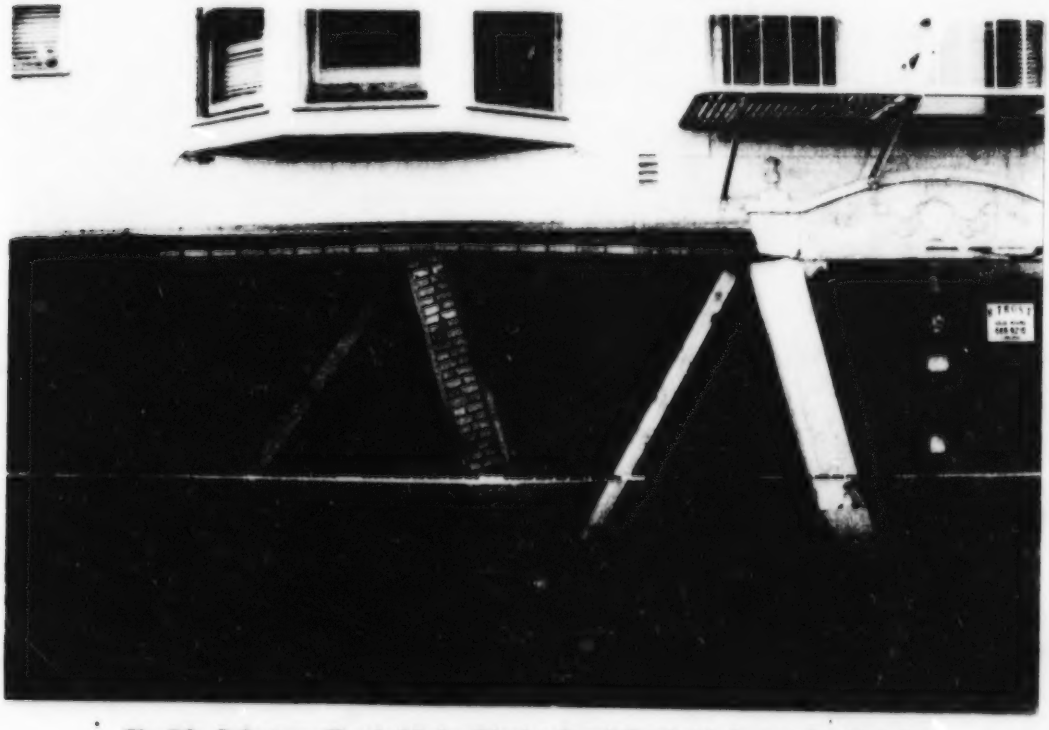

Fig. B9: Soft story effect in Marina District, Beach/Broderick Streets, San Francisco

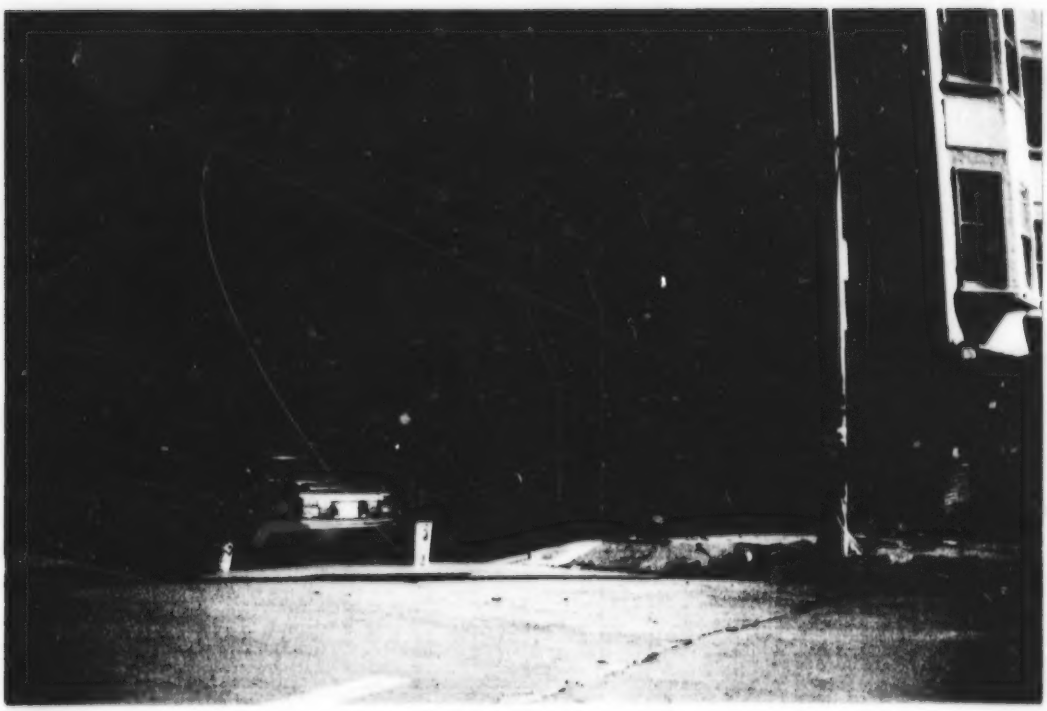

Fig. B10: Another example of soft story effect on Jefferson St., Marina District, San Francisco. Note horizontal boards on posts and over the garage doors

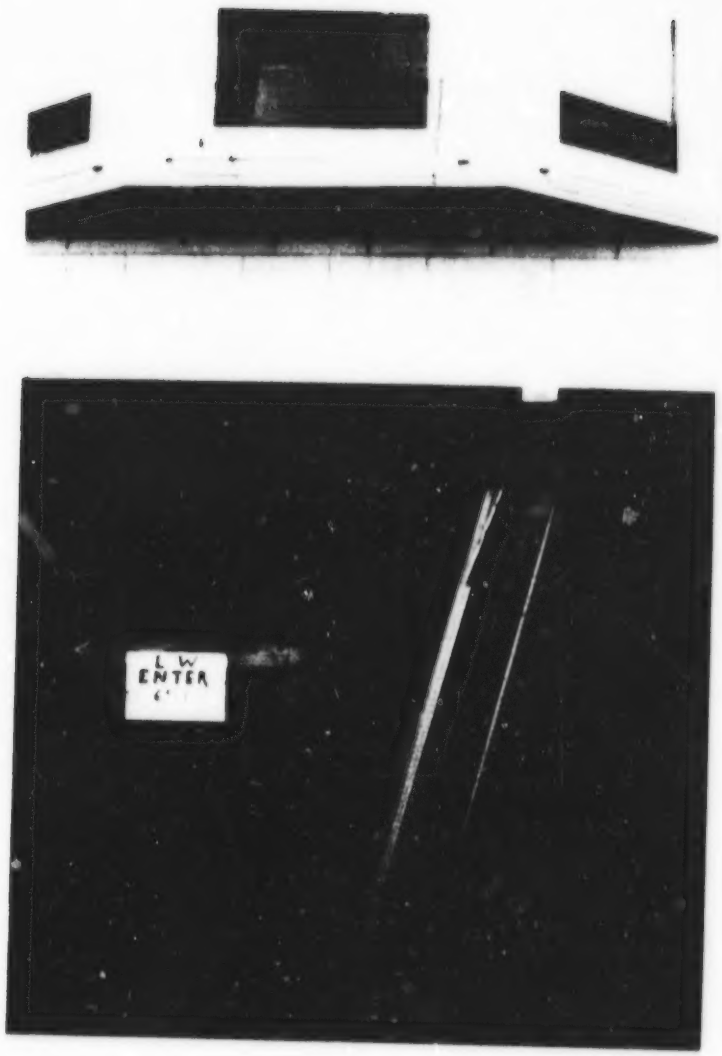

Fig. B11: Inadequate connection between post and second floor framing in the corner 4-storey apartment building in Marina District, San Francisco

Fig. B12: 4-storey buildings with more sheated walls (horizontal boards) sustained less damage and less horizontal shift - Marina District, San Francisco

Fig. B13: 2-storey buildings within block structure experienced some damage - Marina District, San Francisco

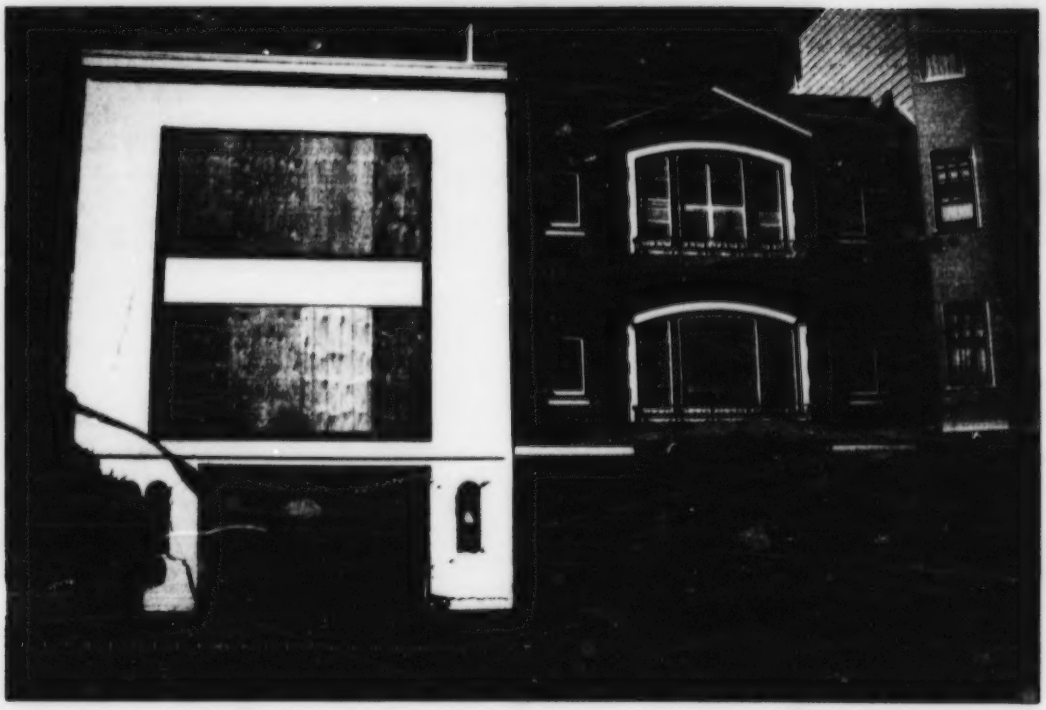

Fig. B14: Large openings (garage doors or windows) invoked some damage in 2-storey buildings in Marina District, San Francisco. Note the shift of the adjacent corner 4-storey building

Fig. B15: Damage to an old unreinforced building structure - I.O.O.F. Building Built in 1893 on East Beach Street in Watsonville

Fig. B16: Demolishing of the heavily damaged unreinforced masonry building on Main Street in Watsonville

Fig. B17: Heavily damaged unreinforced masonry wall building - 39 Main Street, Los Gatos

Fig. B18: Collapsed roof caused damage to the lower floors in the unreinforced masonry building on Campbell Street in Oakland

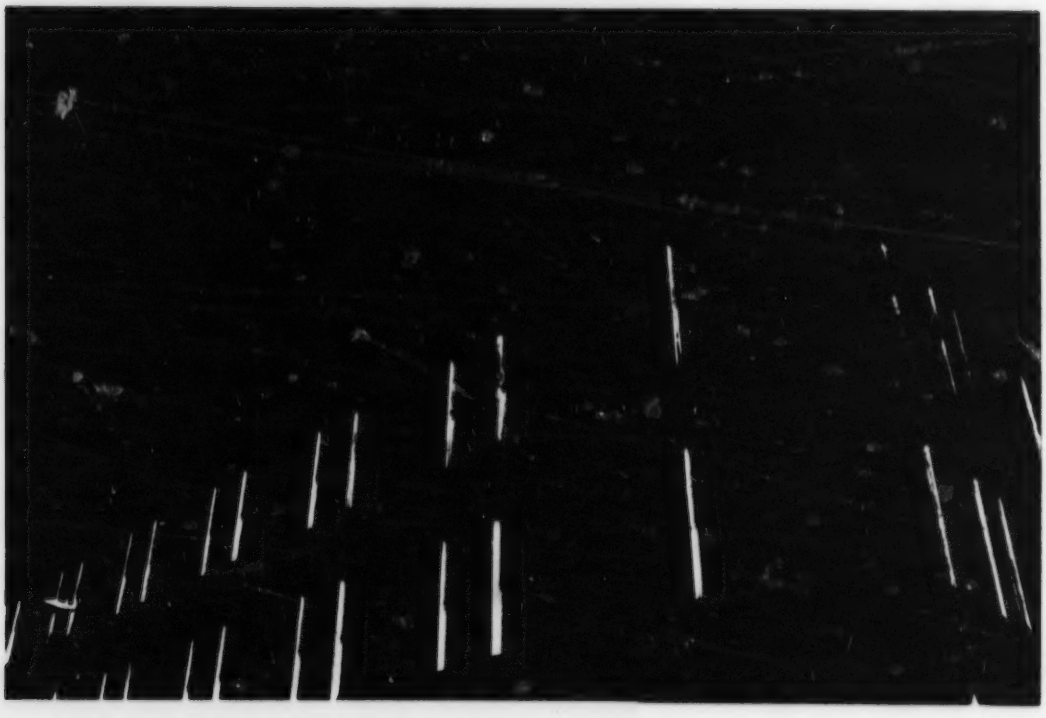

Fig. B19: Parapets fell down in this unreinforced masonry building on Campbell Street in Oakland

Fig. B20: Partially collapsed building due to liquefaction, Aptos, 9.5 km from epicentre

Fig. B21: Ground cracking, Marina District, San Francisco City

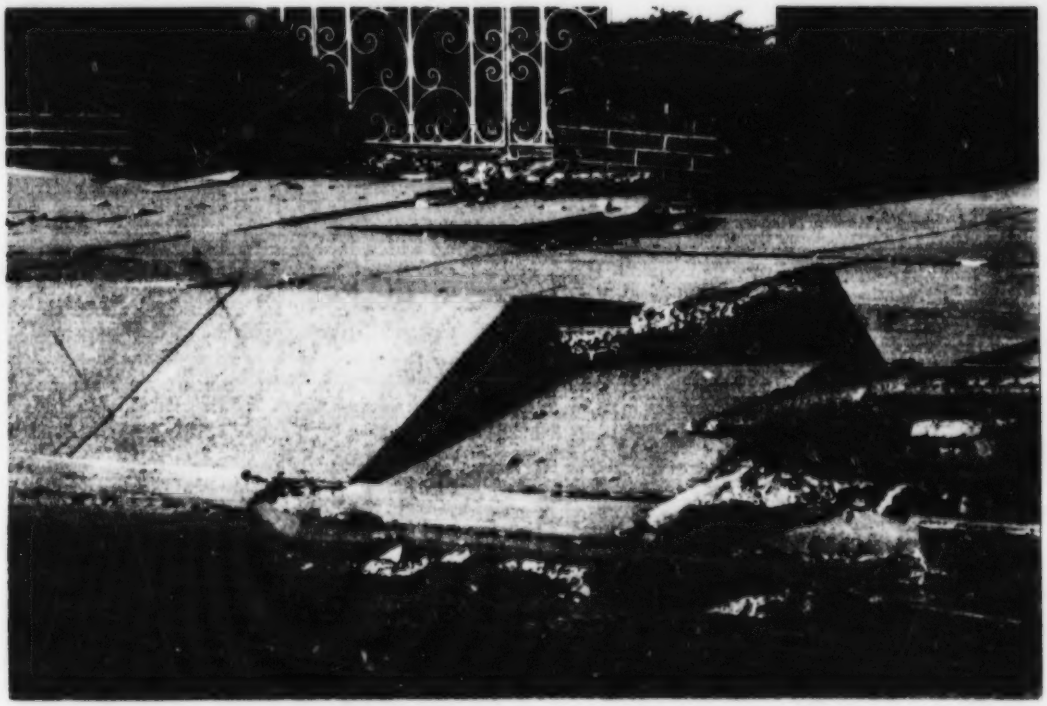

Fig. B22: Buckled pavement, Marina District, San Francisco City

Fig. B23: Sand boil, Marina District, San Francisco City

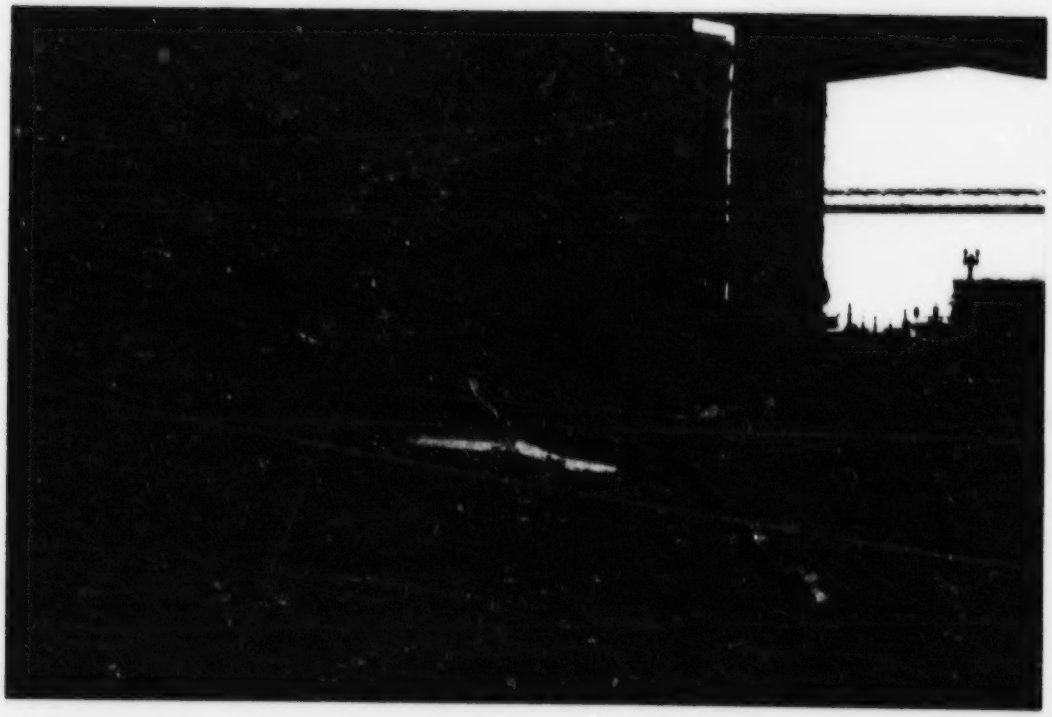

Fig. B24: Differential settlement due to soil densification under the Embarcadero Freeway, San Francisco